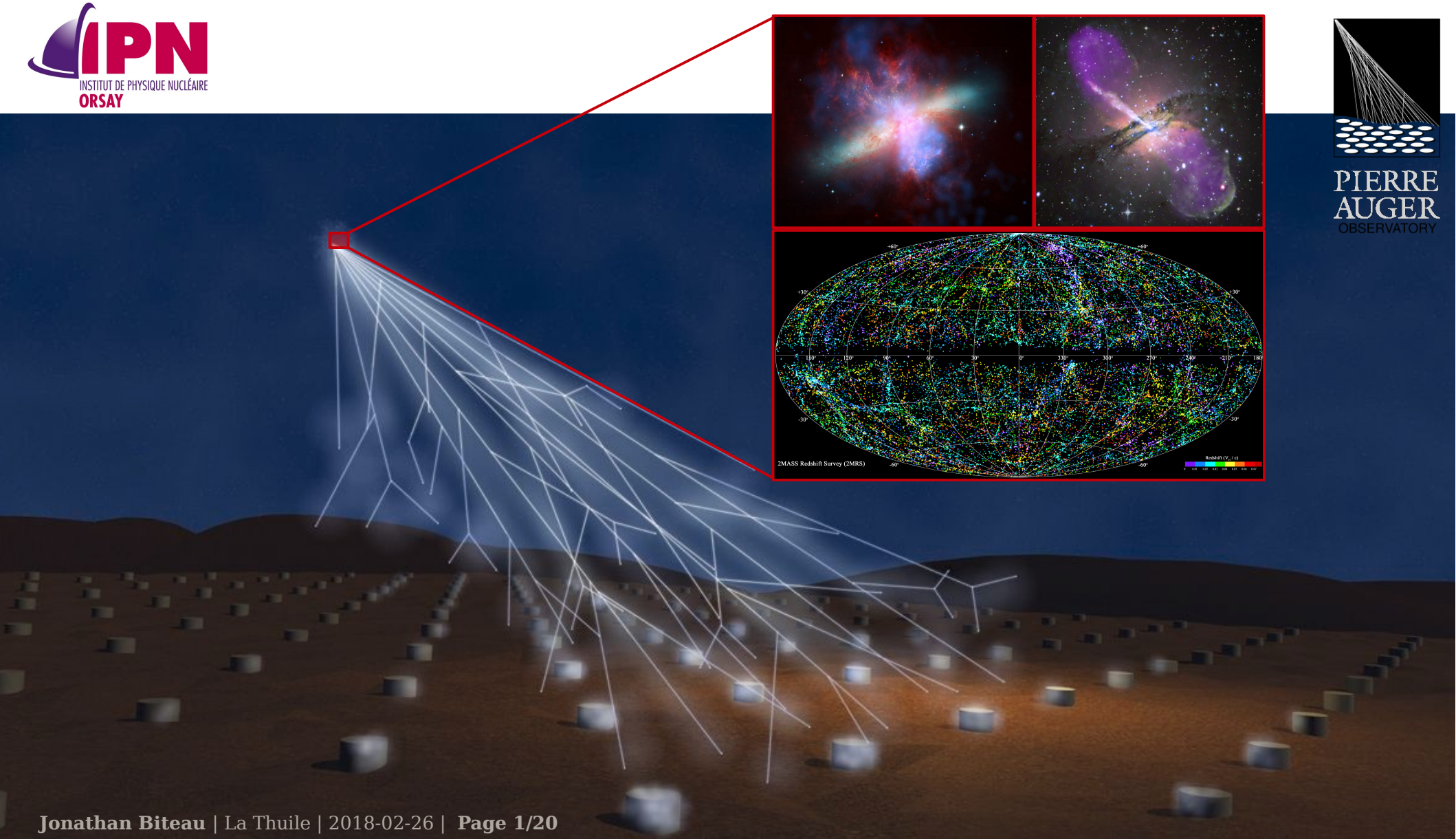
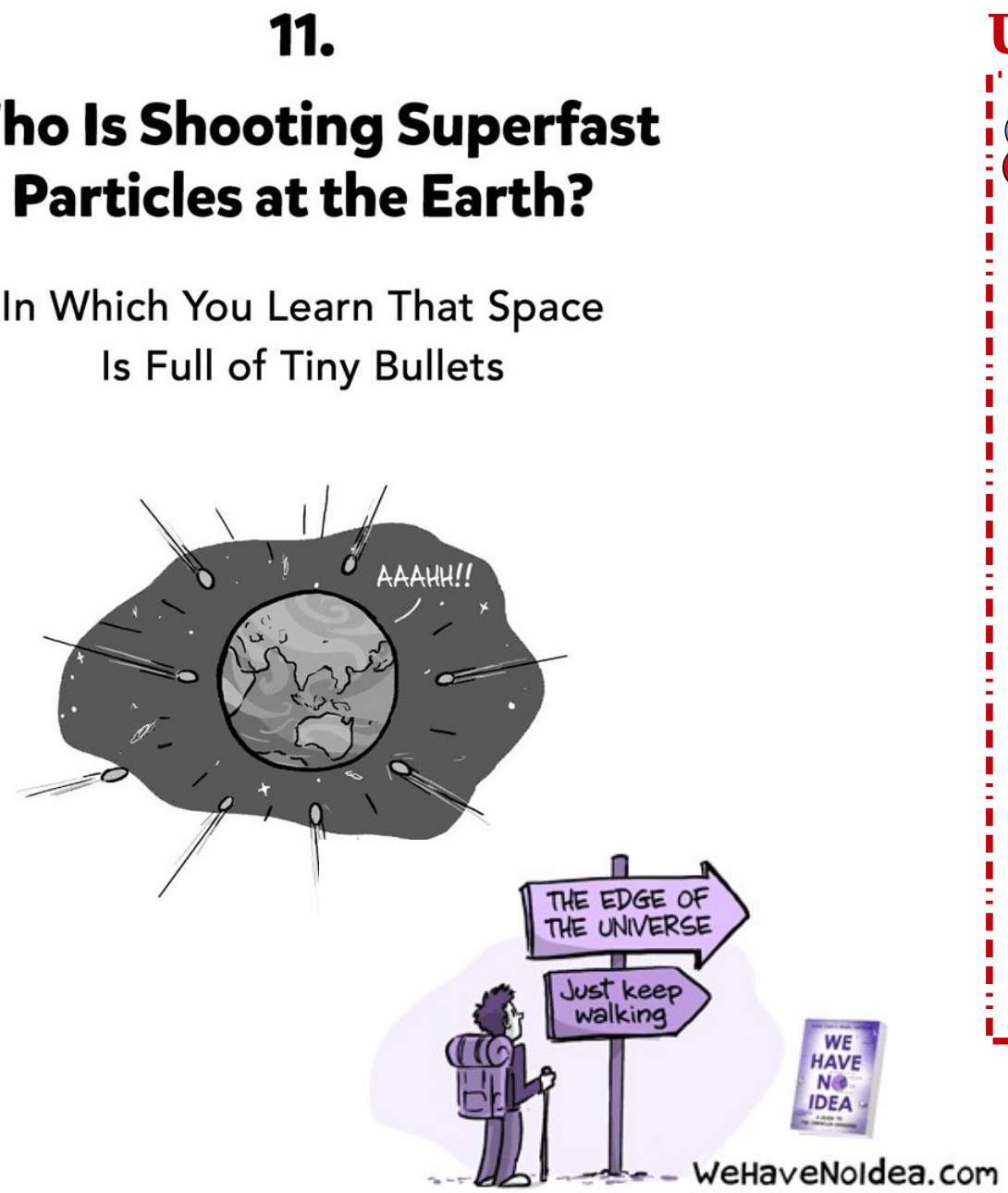
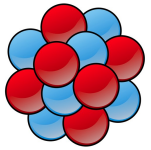
Anisotropies at ultra-high energies
An indication and a discovery



Ultra-high energy cosmic rays



UHECR ID



Nature

Stable nuclei: p to Fe

Energy

from 10^{18} to $>10^{20}$ eV
1 **E**eV to >100 **E**eV

millions to billions TeV!
note: 1 J ~ 6 EeV

Flux

>10 EeV: few / km² / year
>50 EeV: few / km² / century
nearly isotropic

Travel distance

GZK: $^{A}X + \gamma \rightarrow {}^{A}X + \pi^0$ ($e^+ e^-$)
few Gpc (z~0.1-0.2) @ 10 EeV
10-100 Mpc (z<0.05) @ 100 EeV

The Pierre Auger Observatory

Location

West Argentina: 1,400m above sea level
3,000 km² (Luxembourg!)

Components

Atmosphere: calorimeter for the shower of daughter particles

Telescopes: 'image' showers during dark time (**~10% duty cycle**)

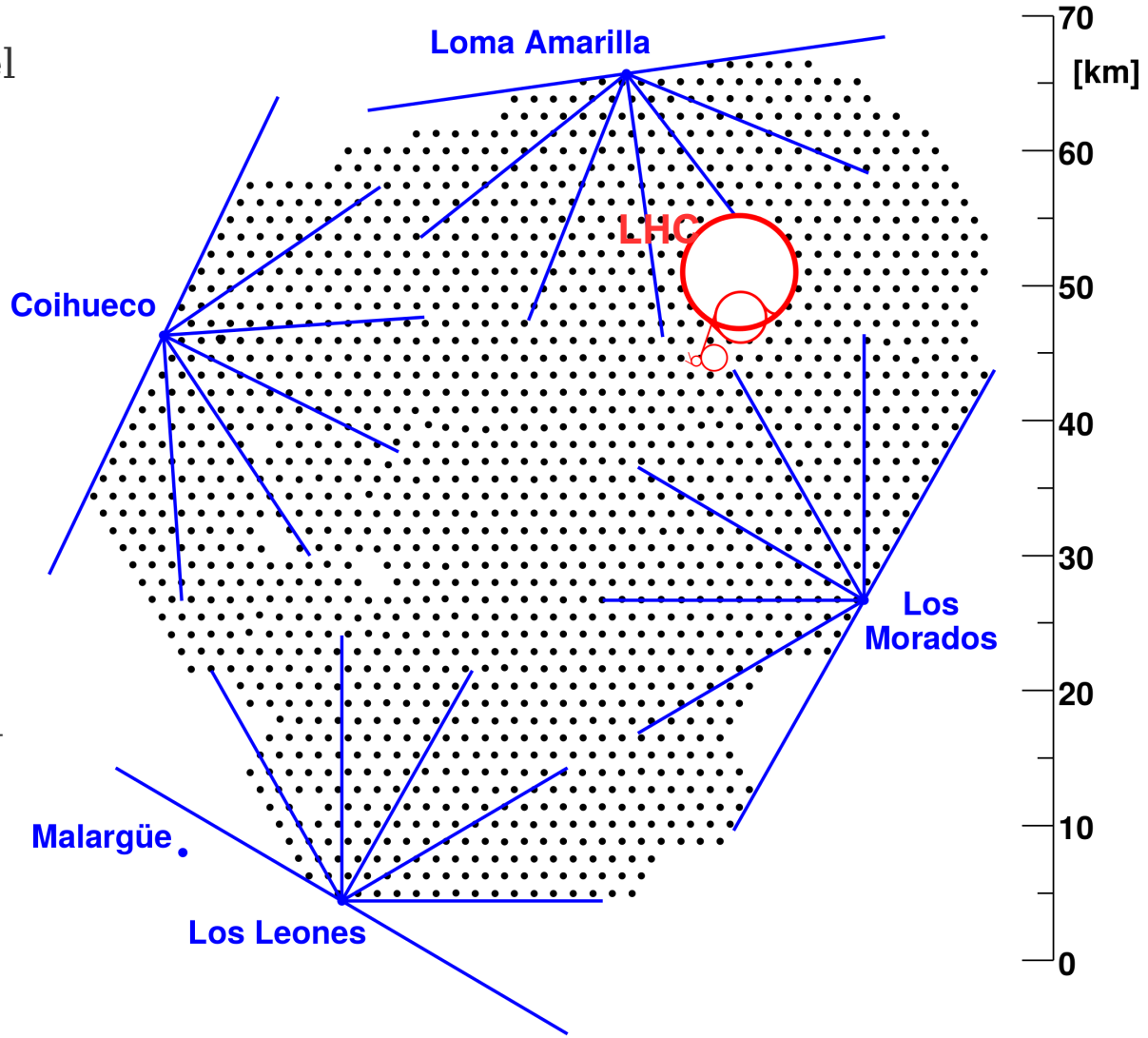
Particle detectors: 'collect' μ/e reaching ground (**~100% duty cycle**)

Fluorescence Telescopes

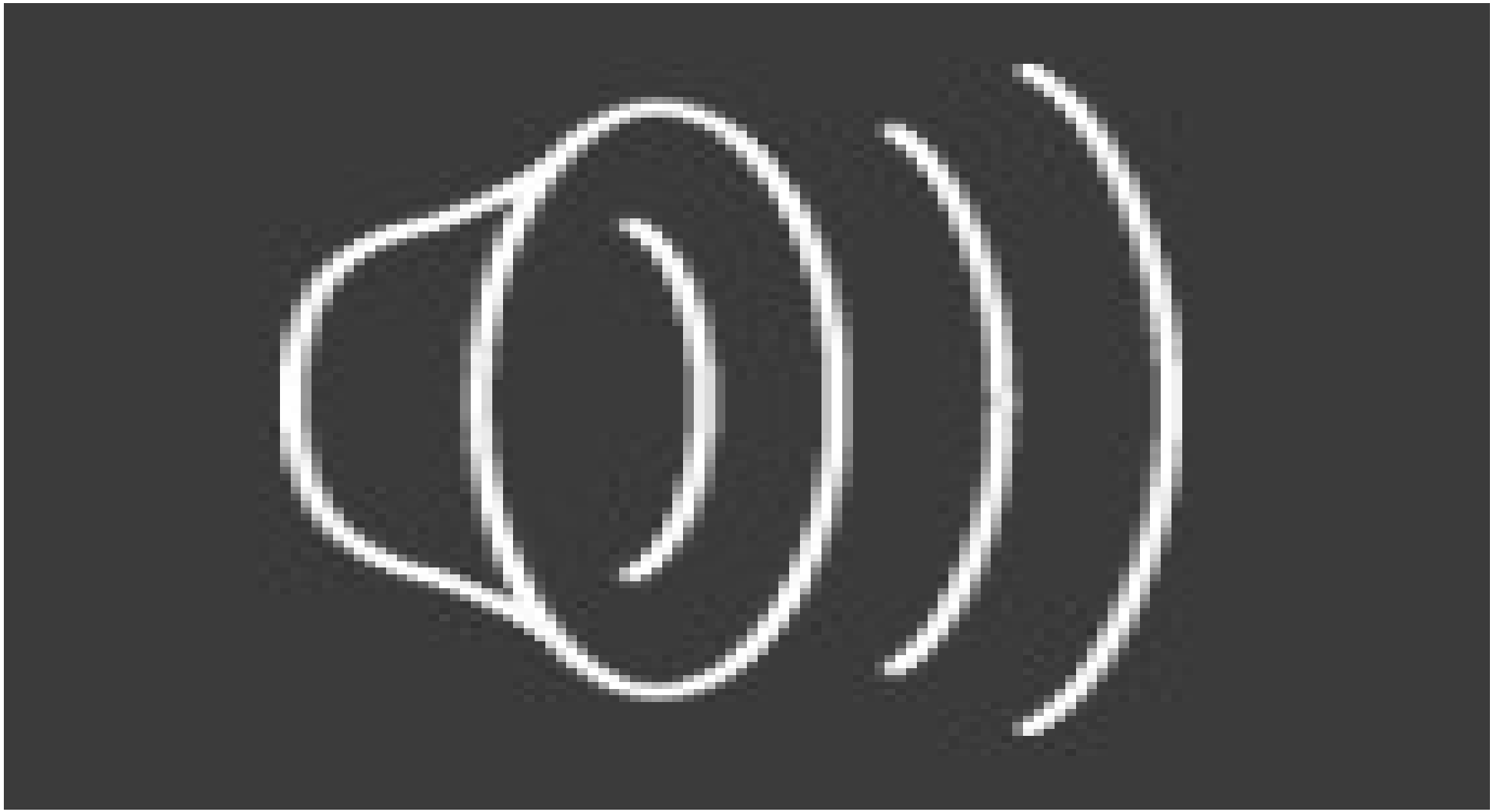
27 fixed cameras (PMTs) in 5 buildings
4 main sites: 6 eyes/site – 30°×30° FoV

Particle Detectors

1600 water-Cherenkov tanks
3 PMTs per tank, spaced by 1,500m
(+infill: 50 spaced by 750m)



Surface array – collecting daughter particles



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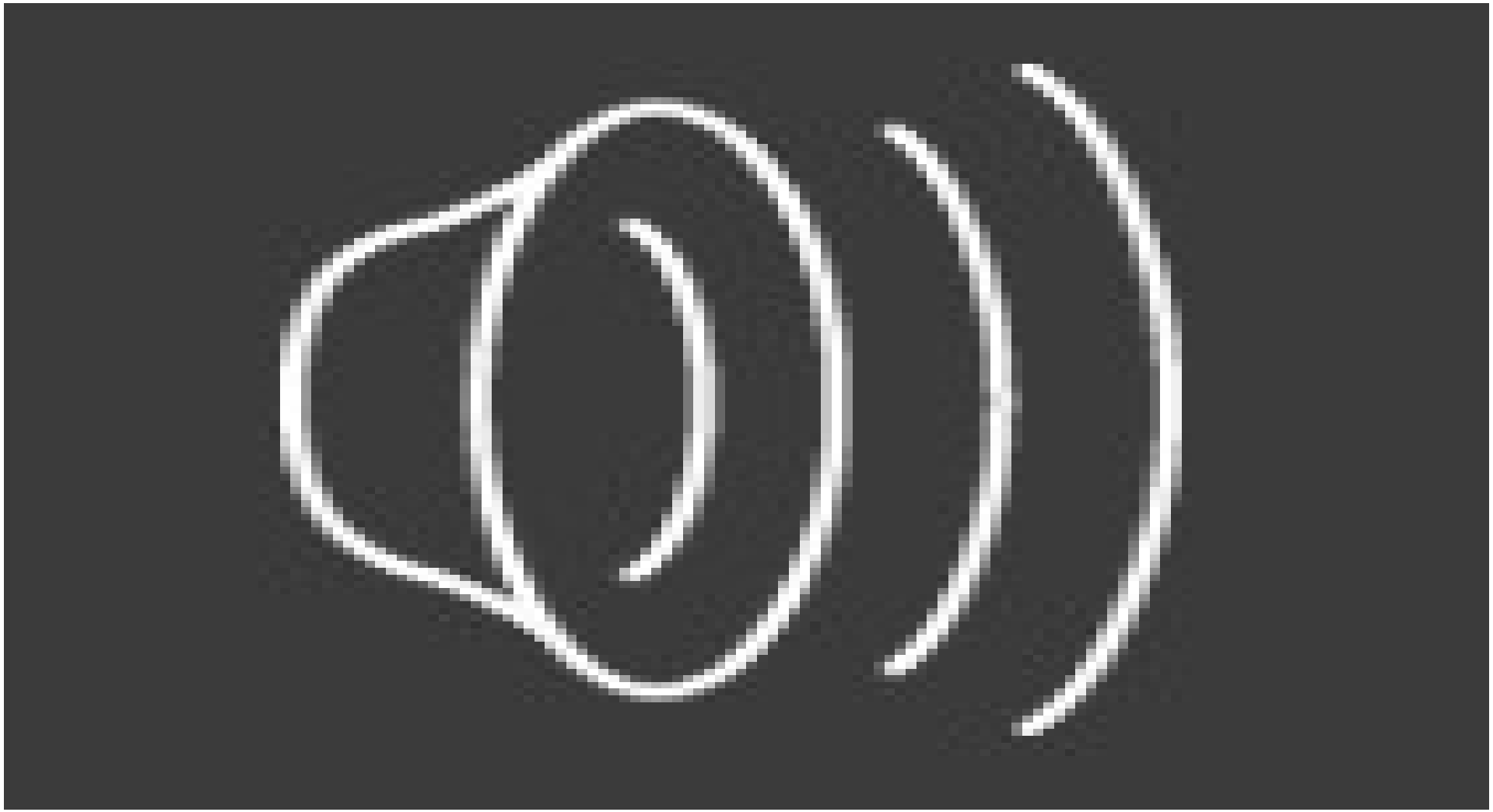
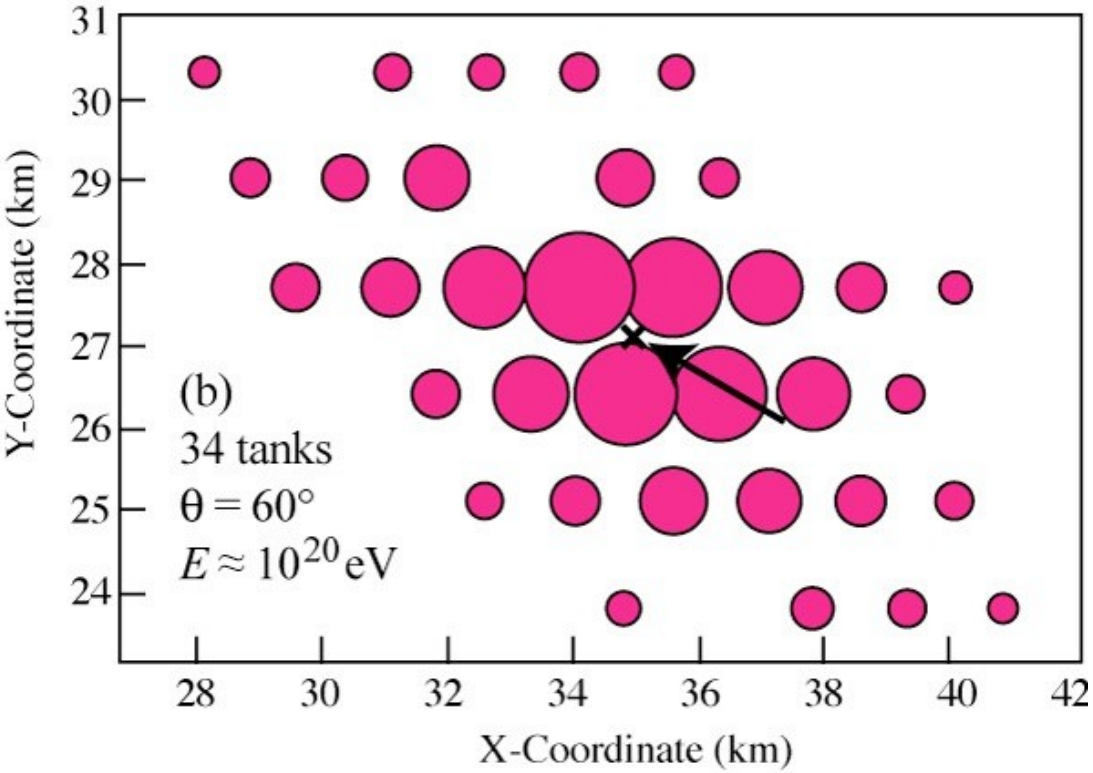


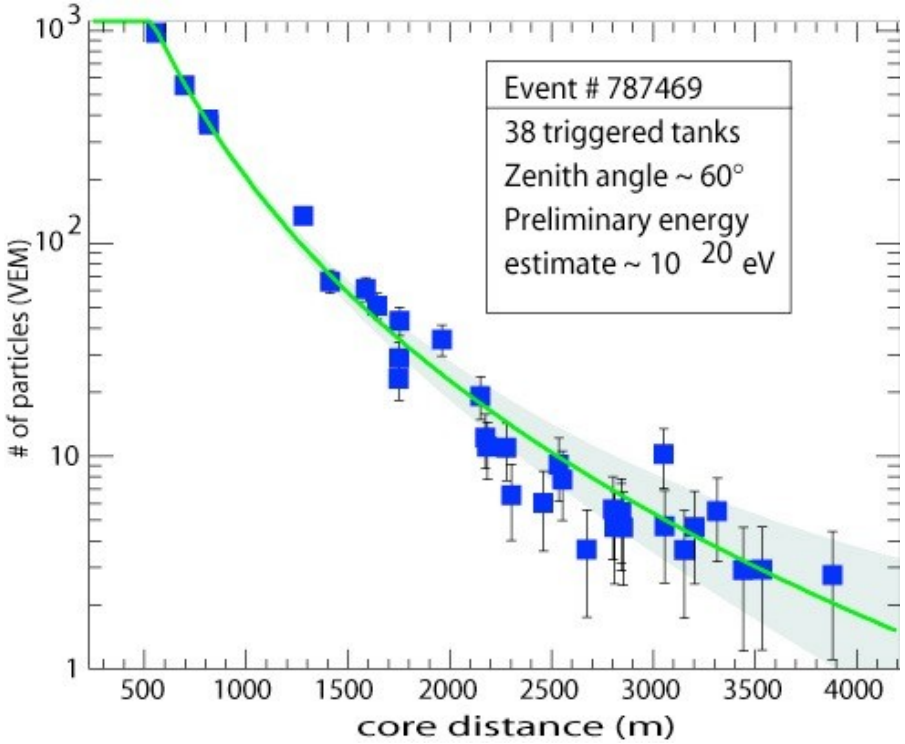
Surface array - performance

Detection of an UHECR event

Trigger of a 'hot' station and its neighboring tanks → 25ns-sampled signal from the array

Array status monitored every minute → number of active detection 'cells' → exposure





Reconstruction of an UHECR event

Charge → energy (stat.~12%) / **Timing → direction** (stat.~0.9°)

Energy calibrated against fluorescence for 'golden-hybrid' subset (sys.~14%)

Large-scale Anisotropy
A discovery

The Pierre Auger Collaboration, Science 357 (2017)

RESEARCH ARTICLE

COSMIC RAYS

Observation of a large-scale anisotropy in the arrival directions of cosmic rays above 8×10^{18} eV

The Pierre Auger Collaboration*†

Rayleigh Analysis in Right Ascension

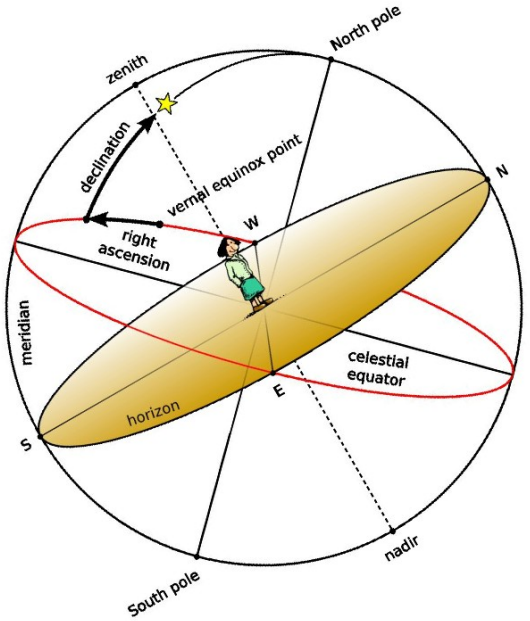
Equatorial coordinate system

Spherical coordinates with z along Earth's rotation axis

→ Right Ascension. (α≡Φ), Declination (δ≡π/2-θ)

Directional exposure constant in R.A.

. Sidereal day: 23h 56m 4s
→ solar / sidereal: control of accuracy (e.g. correction for density. and pressure variations vs hour of the day)



Rayleigh analysis in R.A.

Pierre Auger Collab. 2012

$$a_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos \alpha_i$$

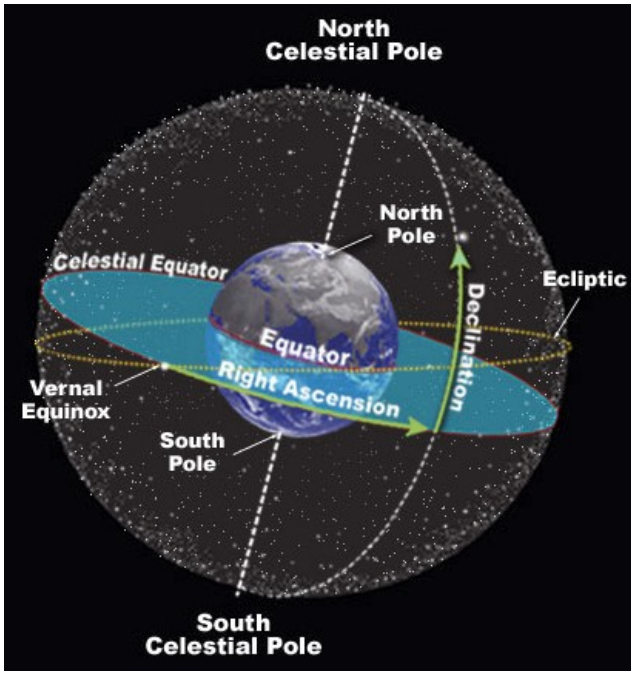
$$b_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin \alpha_i$$

$$r_\alpha = \sqrt{a_\alpha^2 + b_\alpha^2}$$

$$\tan \varphi_\alpha = \frac{b_\alpha}{a_\alpha}$$

α_i: R.A. of the event, w_i=array non-uniformity / tilt ($N=\Sigma w_i$)

→ r, φ: amplitude, phase of the 1st harmonic in R.A.



Deviation from isotropy

Linsley 1975

$$P(r_\alpha) = \exp(-\mathcal{N} r_\alpha^2/4)$$ → **p-value** for a single tested dataset

Rayleigh analysis in Right Ascension

Study in two energy bins

Array fully efficient up to 80° > 4 EeV

4-8 EeV: ~82,000 events

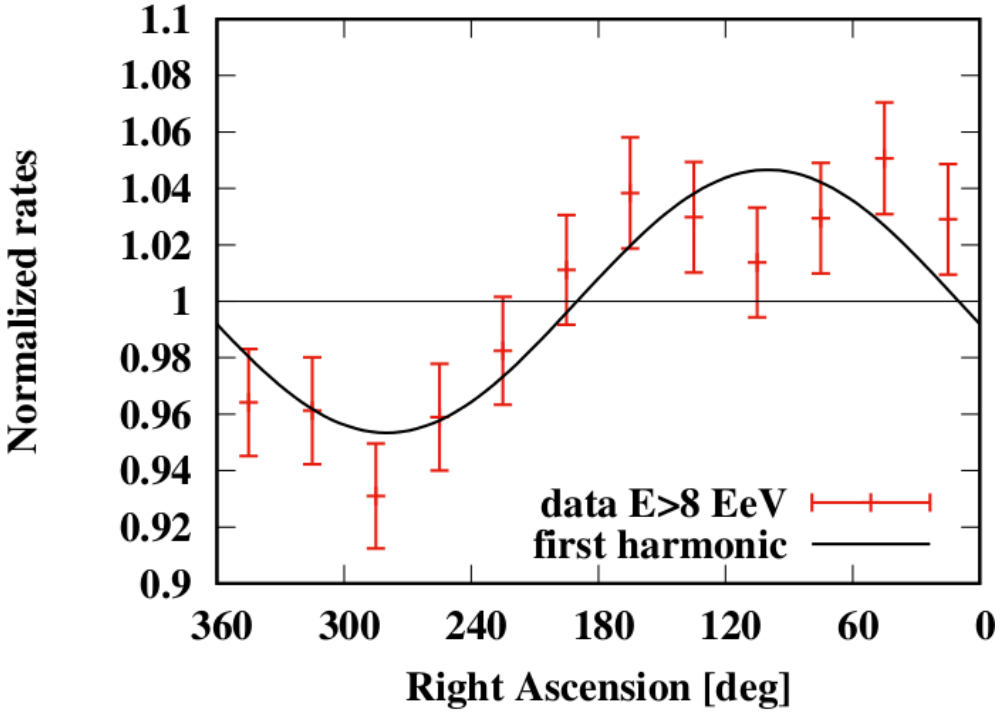
φ = 80±60°, r < 1.2% (95% C.L.)

→ no significant modulation

>8 EeV: ~32,000 events

φ = 100±10°, r = 4.7%±0.8%

→ **local p=2.6 × 10⁻⁸!**

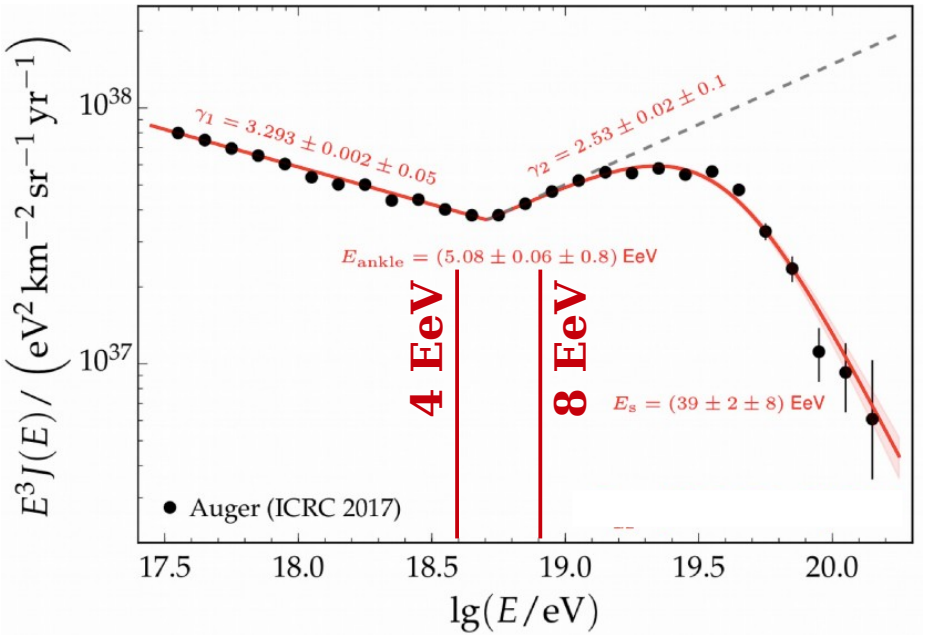


Penalization for the energy scan

Study in 2 independent energy bins

→ global p-value of 5 × 10⁻⁸

→ first harmonic significant at the **5.4σ level**

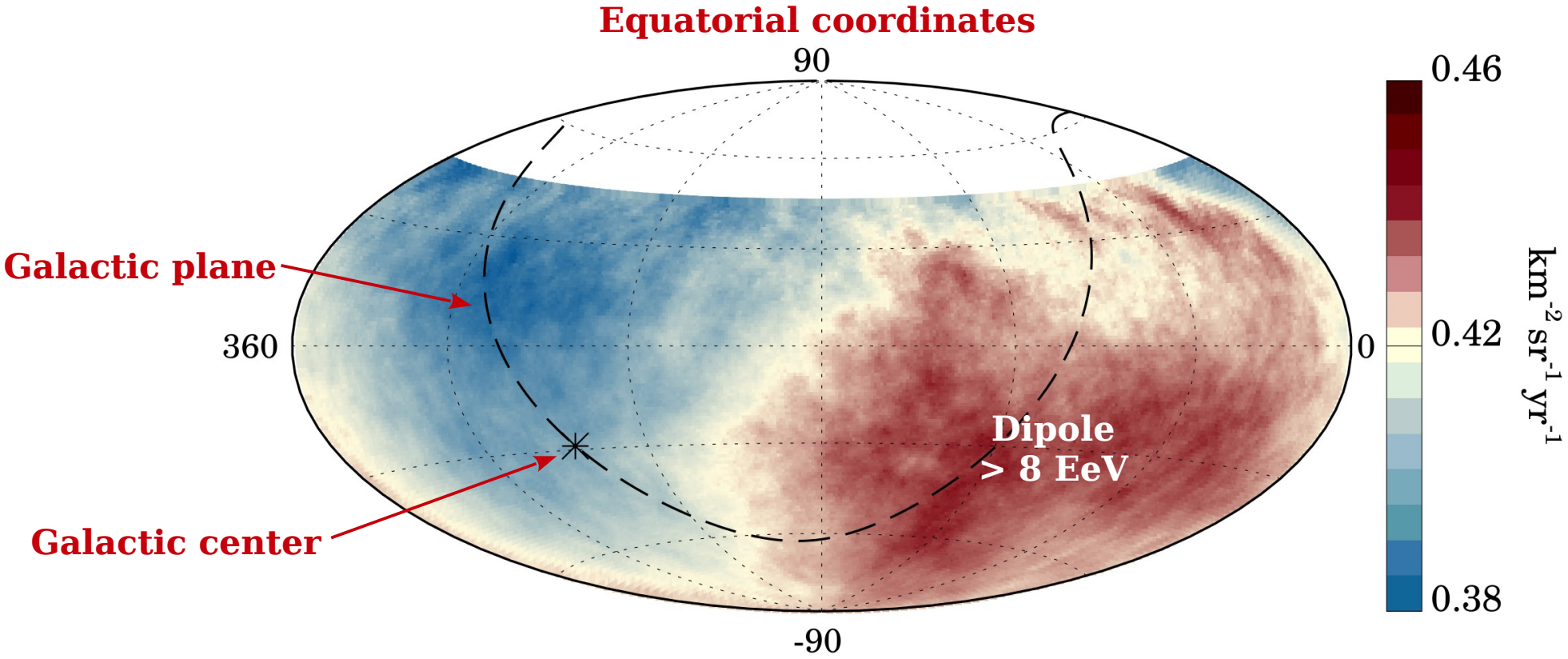


Combining Right Ascension and Azimuthal

Amplitude of the dipole

d = 6.5%±1.0% → 10× larger than from proper motion wrt large scale structures!

→ astrophysical sources with anisotropic flux distribution?



Direction of the dipole

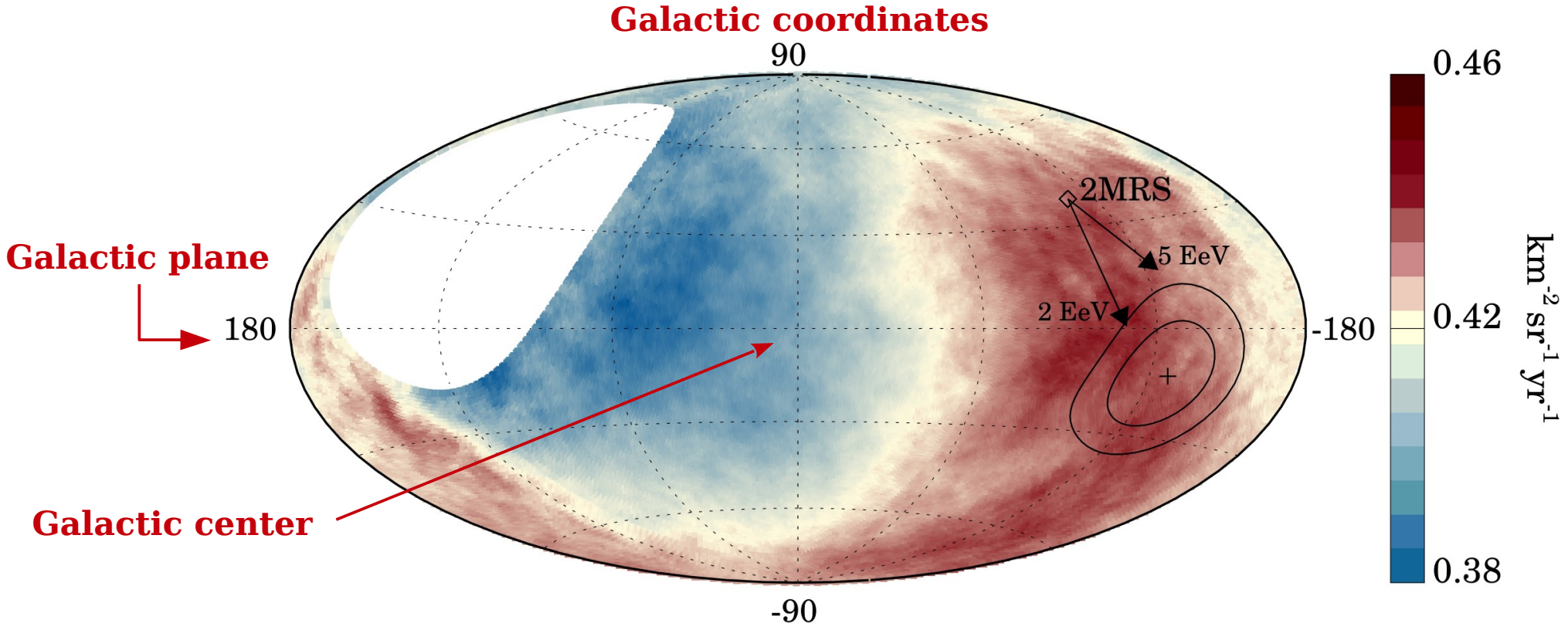
125° ± 12° from the Galactic center → hard to reconcile with Galactic origin, unless quite peculiar structure of the Galactic magnetic field (center = sink → anti-center? Eichler+16)

UHECR & 2MRS dipoles

Effect of Galactic magnetic field (GMF)

Deflections in GMF: a few 10° Z (E / 10 EeV)$^{-1}$, with <Z>~2-5 at ~10 EeV (fluorescence)

Test realizations: use the GMF model of Jansson & Farrar 12 → **good direction!**



Conclusion

First detection >5σ of a large-scale anisotropy > 8 EeV

Direction & amplitude consistent with an extragalactic origin → **All / which galaxies???**

Which galaxies?
An indication

The Astrophysical Journal Letters, 00:000000 (9pp), 2018 Month Day

An Indication of Anisotropy in Arrival Directions of Ultra-high-energy Cosmic Rays through Comparison to the Flux Pattern of Extragalactic Gamma-Ray Sources

The Pierre Auger Collaboration, accepted in ApJL (2018)

A multimessenger approach

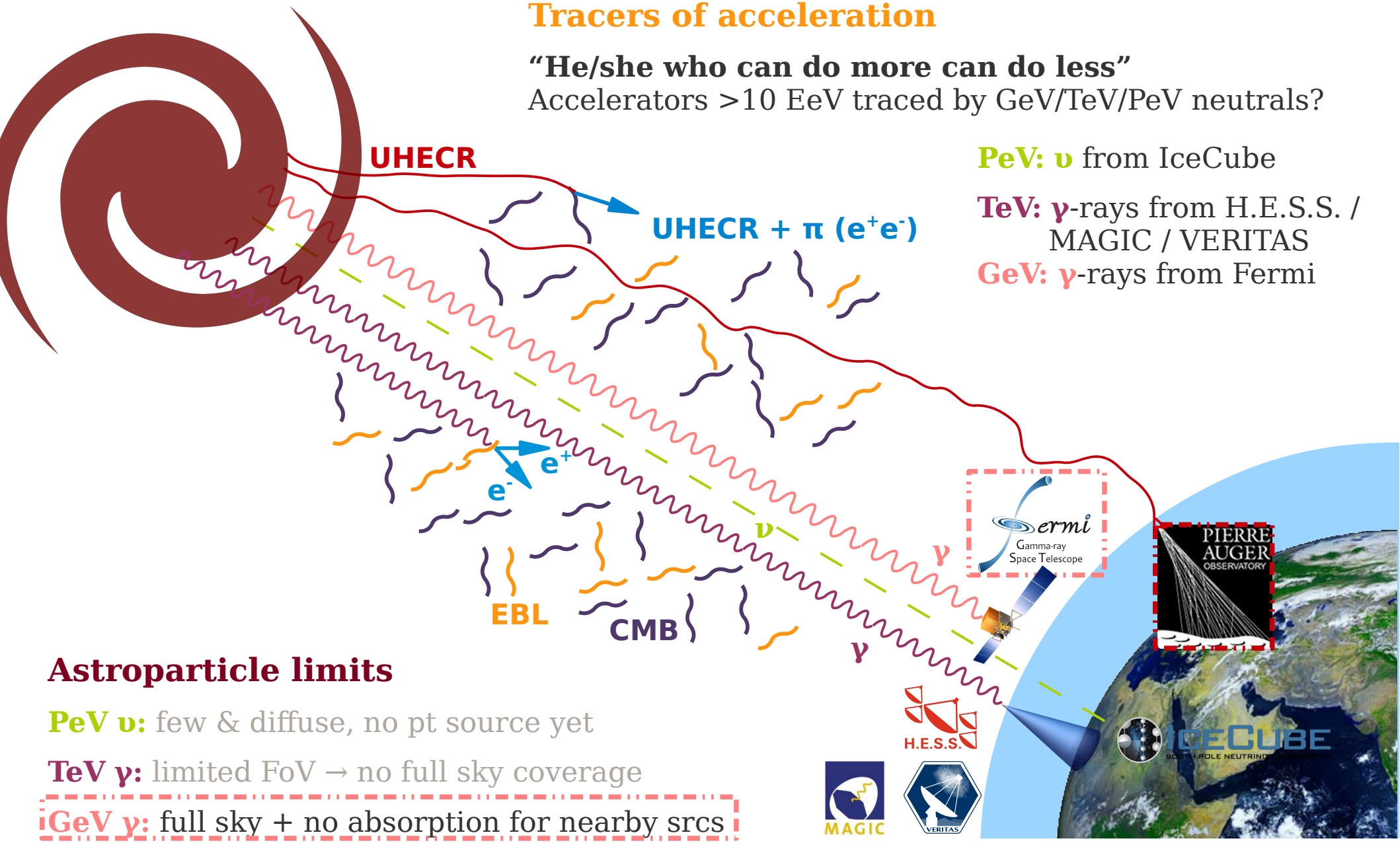
Tracers of acceleration

“He/she who can do more can do less”
Accelerators >10 EeV traced by GeV/TeV/PeV neutrals?

PeV: υ from IceCube

TeV: γ-rays from H.E.S.S. / MAGIC / VERITAS

GeV: γ-rays from Fermi



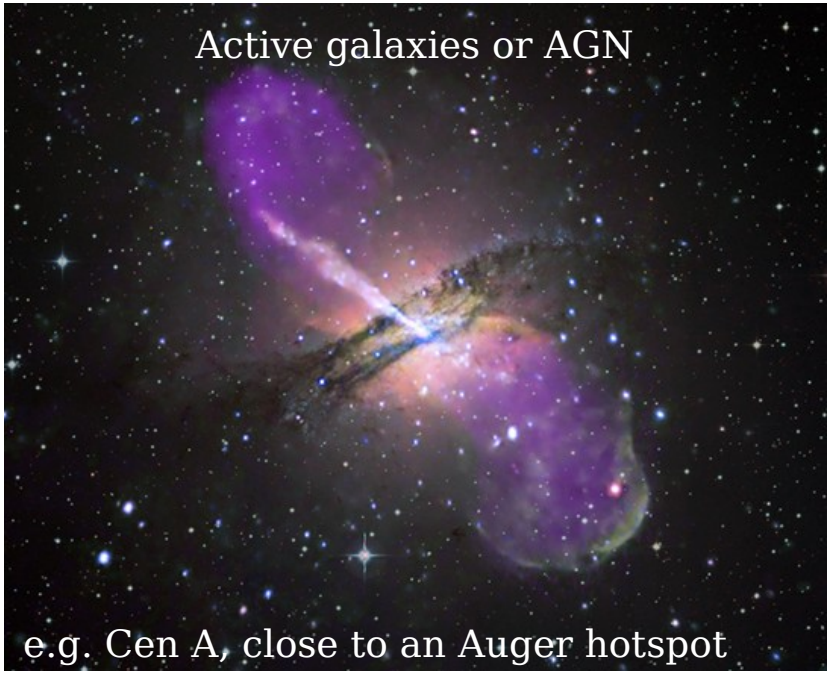
Astroparticle limits

PeV υ: few & diffuse, no pt source yet

TeV γ: limited FoV → no full sky coverage

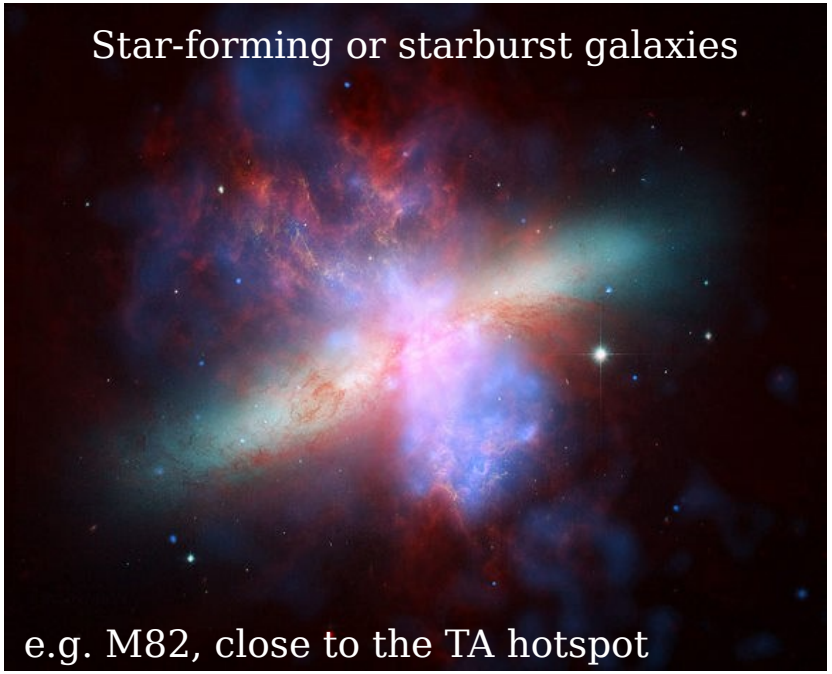
GeV γ: full sky + no absorption for nearby srcs

AGNs and SBGs in our vicinity



AGNs from the 2FHL Catalog
(*Fermi*-LAT, > 50 GeV)
within 250 Mpc

Ackermann+ 16



'Starbursts' from *Fermi*-LAT search list
(HCN survey) within 250 Mpc
with radio flux > 0.3 Jy

Gao & Salomon 05

Assumption: UHECR flux ∝ non-thermal photon flux

Analysis: unbinned maximum-likelihood analysis vs isotropy
Sky model: [**α**×sources + (1-**α**)×isotropic] ⊗ Fisher(**θ**)

Note: inspired from Pierre Auger Collaboration 2011 but differs from most past UHECR studies: doesn't assume that sources are 'standard' candles

Result of the scan: the starburst indication!

Starburst galaxies

> 39 EeV: N~900 events, TS~25

α=10%, θ=13°

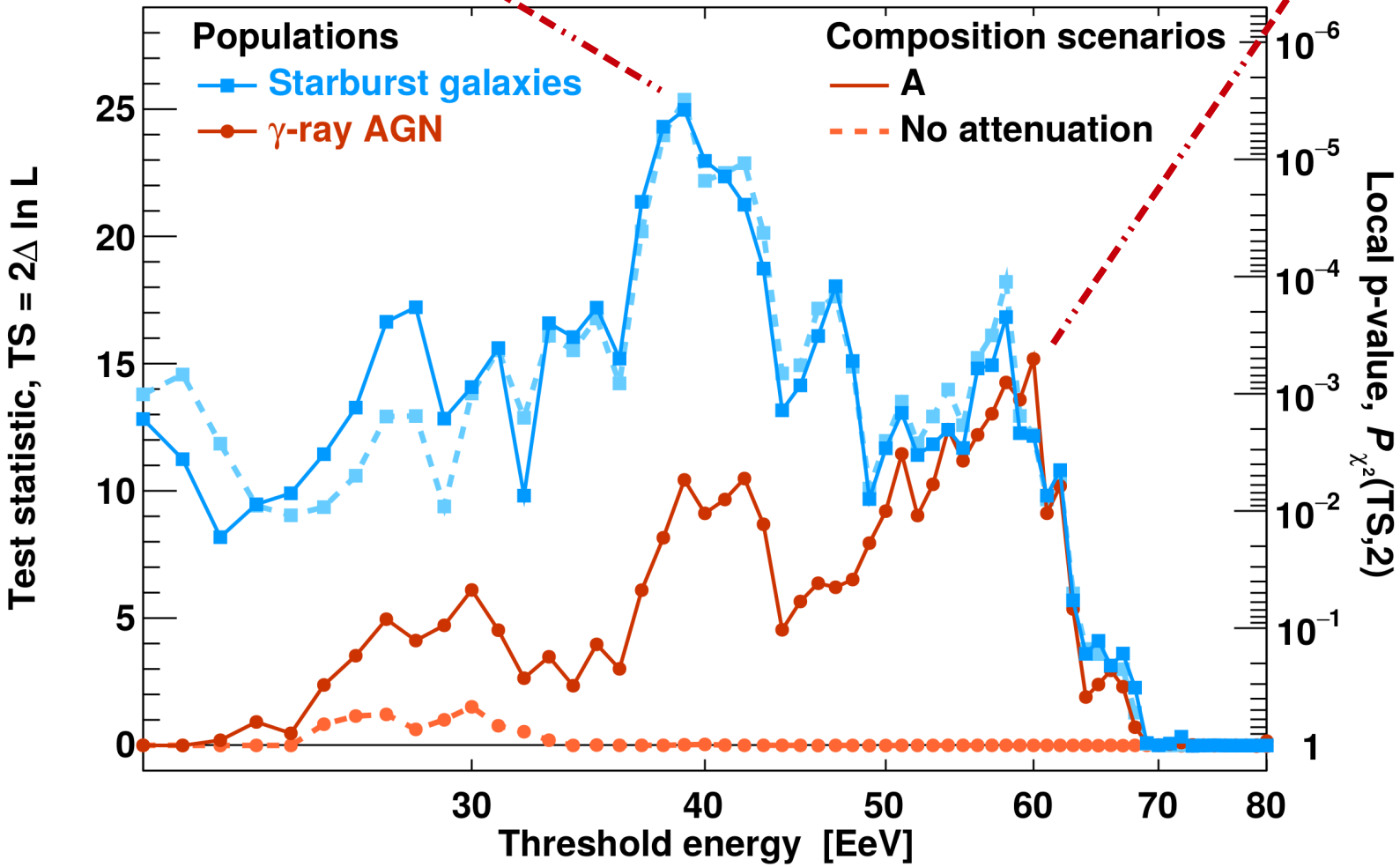
2 free par. + E-scan → 4.0σ

Active galaxies

> 60 EeV: N~180 events, TS=15

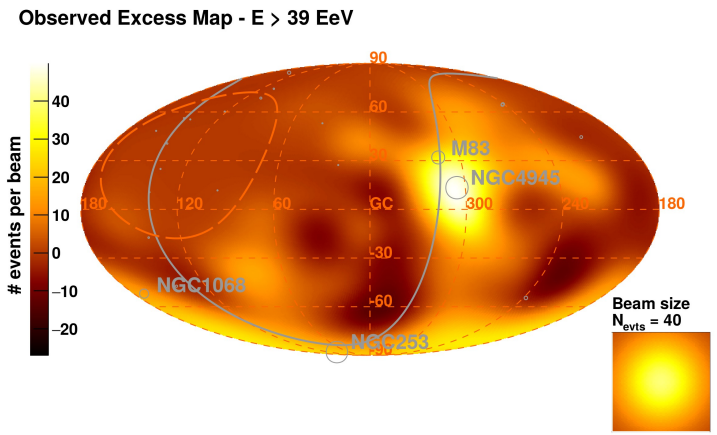
α=7%, θ=7°

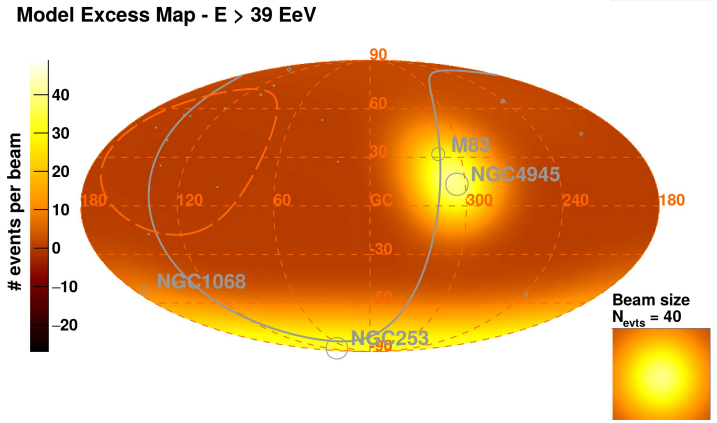
2 free par. + E-scan → 2.7σ

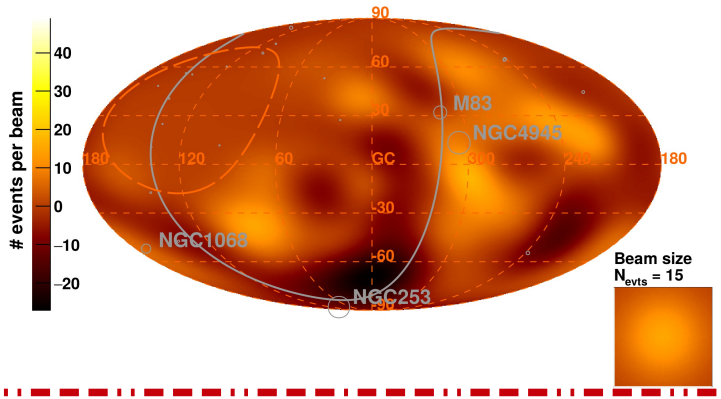


Observations vs Expectations

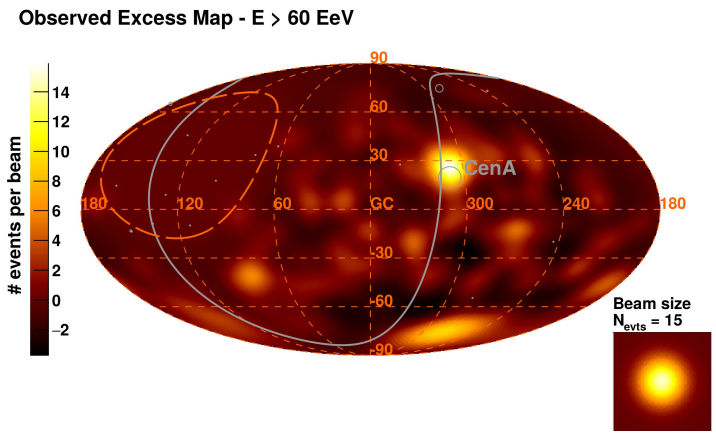
Starburst galaxies

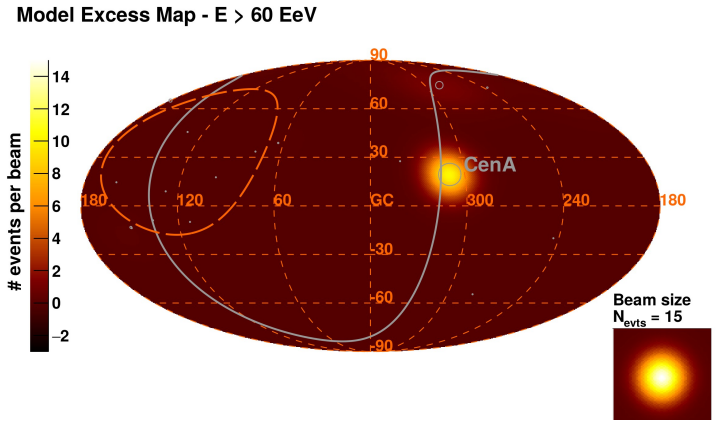


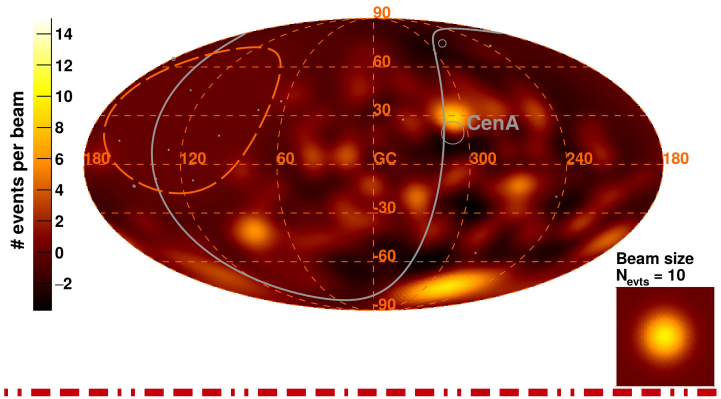




Active galaxies







Starburst galaxies - best-fit parameters

Anisotropic fraction

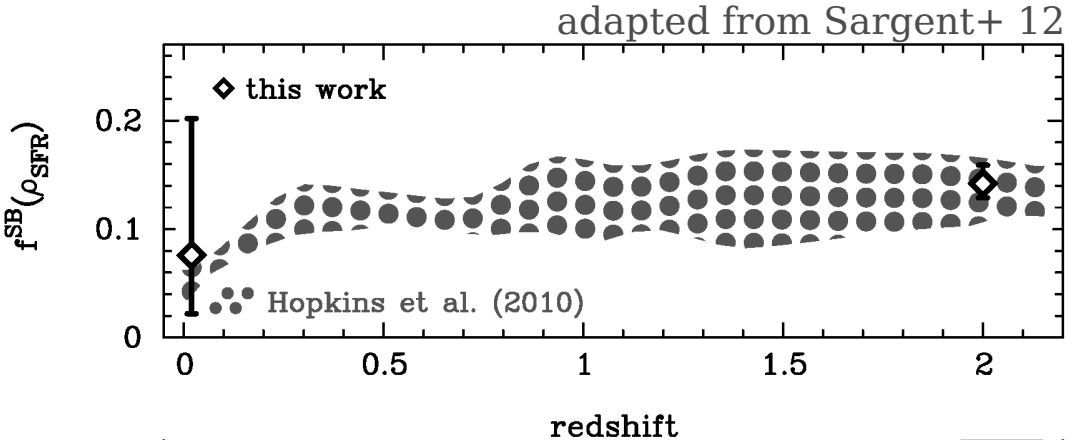
10% of UHECR events correlating with position and flux of starbursts

Other 90%? Heavier nuclei deflected further away? Unresolved sources?

Note: Starburst contribution to local starformation rate: 5-20% (Sargent+ 12)

→ Are starbursts the tip of the iceberg?

adapted from Sargent+ 12



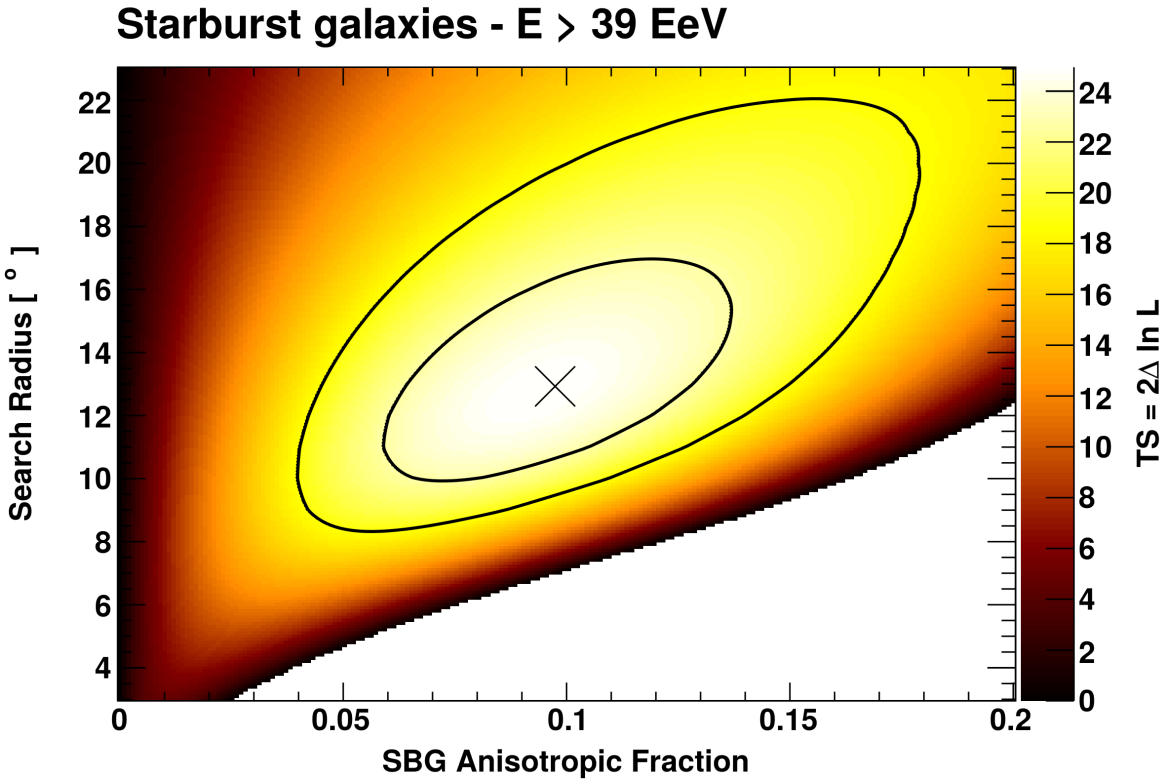
Search radius

Simulations of 3 tested composition scenarios through the Galactic magnetic field of Jansson & Farrar 12

. 2 CNO-dominated scenarios → ~25°
. 1 p-dominated scenario → ~5°

→ reconstructed parameters from sims bracket θ~13°

Composition > 40 EeV?



Beyond

Auger upgrade

Highest energies: components

. 3.8 m² scintillators on each water-cherenkov tank
. upgraded electronics + extra PMT (dynamic range)

→ improved characterization of electromagnetic & muonic components of the shower

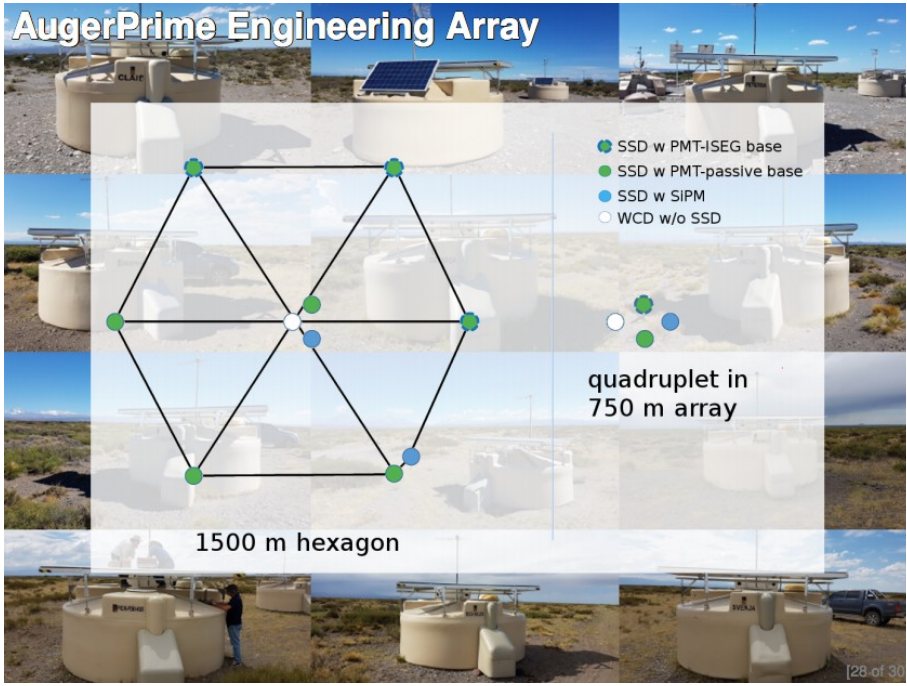
→ $N_{\mu}(E)$ correlated to $X_{max}(E)$ → **better compo.**

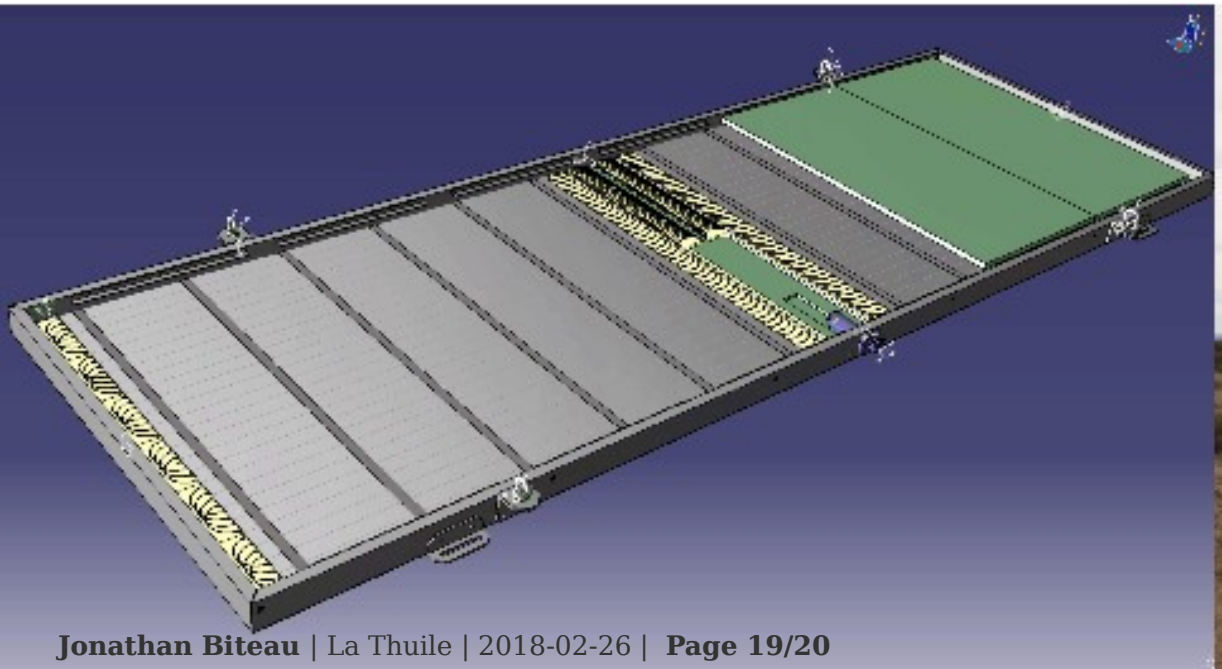
e.g. Parra +16

Lower energies: components

. Burried muon counters in infill array (AMIGA)

. Increased fluorescence uptime





Back to the old mission:

Who Is Shooting Superfast Particles at the Earth?

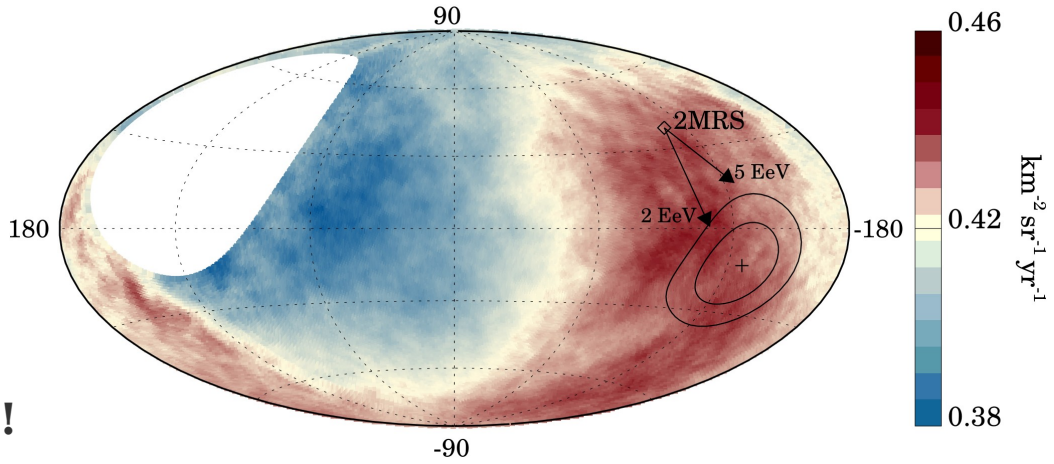
First harmonic study > 8 EeV

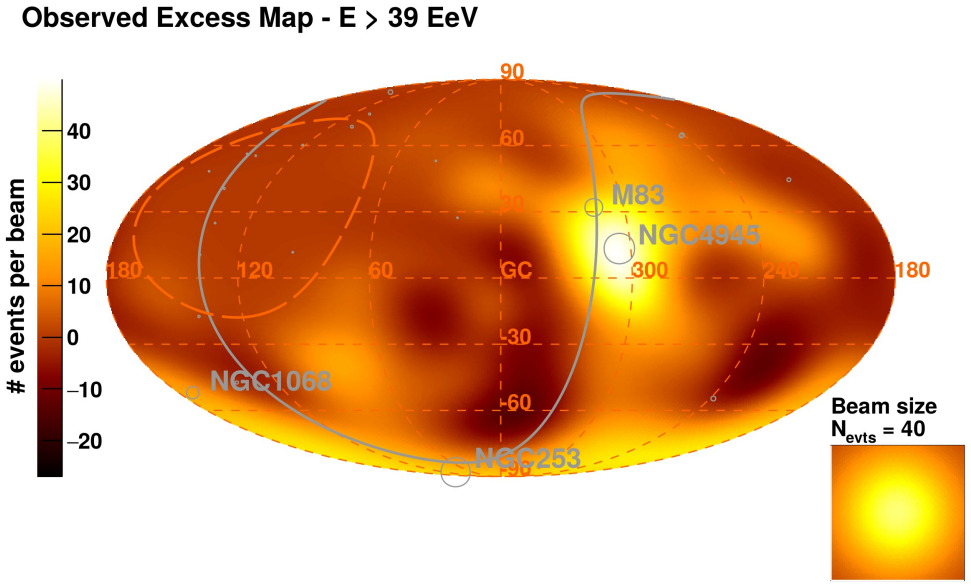
. Collection of > 30,000 events
→ **5.4σ anisotropy**

1st order spherical expansion

. 6.5% dipole compatible with galaxy distrib.

→ **1st obs. evidence of extragalactic origin!**





Max-likelihood analysis > 40 EeV

. Collection of ~900 events
→ **4.0σ starburst-based anisotropy**

We still don't know the sources!

. Starbursts only preferred to other galaxies by ~3σ

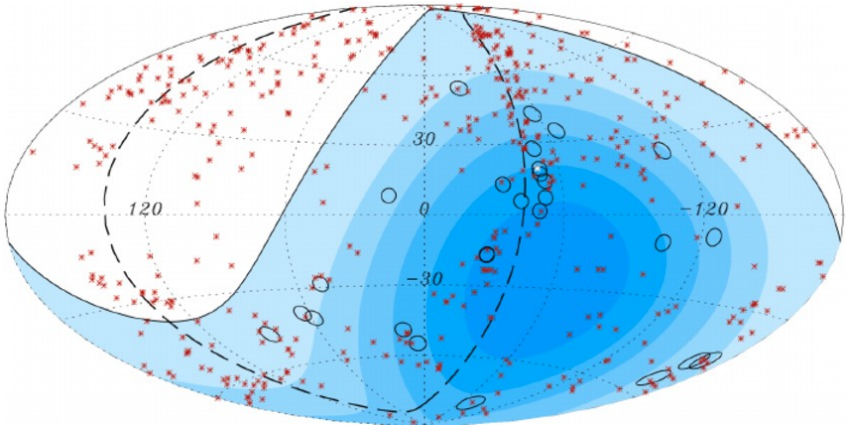
. **More to come**: models (magnetic fields) current data (Auger+TA), upgrades!

Backup

Side note: the VCV trauma

2007 tentative correlation with VCV

Pierre Auger Collab., Science 2007



VCV: Véron-Cetty & Véron compilation of AGN

'Standard candle' approach: 2-pt correlation scan over search radius around evts and source distance

20/27 events > 57 EeV within 3.2° of 21 galaxies within 75 Mpc → **p-value = 0.2% (3σ)**

Good fraction of the signal from clustering of 10 evts around **Cen A / M 83 / NGC 4945 group**

Latest update of this analysis (2014) → **2σ**

Why did the signal drop?

'Standard candle' approach
→ strong incompleteness effect (see Farrar +09)
→ limit of infinite # of srcs/evts: signal drops!

+ Low statistics → more subject to fluctuations

Current analysis any different?

2-pt correl. → max-likelihood (no ∞ stat. issue)

Flux weight + volume limit → less affected by missed faint sources (checked with ≠ SB cat.)

27 events → 894 events